Origin of the unusually low nitrogen abundances in young populations of the Large Magellanic Cloud

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ABSTRACT

It is a longstanding problem that HII regions and very young stellar populations in the Large Magellanic Cloud (LMC) have the nitrogen abundances ([N/H]) by a factor of ~ 7 lower than the solar value. We here discuss a new scenario in which the observed unusually low nitrogen abundances can be closely associated with recent collision and subsequent accretion of H I high velocity clouds (HVCs) that surround the Galaxy and have low nitrogen abundances. We show that if the observed low [N/H] is limited to very young stars with ages less than $\sim 10^7$ yr, then the collision/accretion rate of the HVCs onto the LMC needs to be $\sim 0.2 \mathrm{M}_{\odot}$ yr^{-1} (corresponding to the total HVC mass of $10^6 - 10^7 \mathrm{M}_{\odot}$) to dilute the original interstellar medium (ISM) before star formation. The required accretion rate means that even if the typical mass of HVCs accreted onto the LMC is $\sim 10^7 \mathrm{M}_{\odot}$, the Galaxy needs to have ~ 2500 massive HVCs within the LMC's orbital radius with respect to the Galactic center. The required rather large number of massive HVCs drives us to suggest that the HVCs are not likely to efficiently dilute the ISM of the LMC and consequently lower the [N/H]. We thus suggest the transfer of gas with low [N/H] from the Small Magellanic Cloud (SMC) to the LMC as a promising scenario that can explain the observed low [N/H].

Subject headings: Galaxy: halo – (galaxies): Magellanic Clouds – galaxies: evolution – galaxies: halos – galaxies: abundances

1. Introduction

Chemical abundances in gaseous and stellar components of the LMC and the SMC have provide many clues to formation and evolution of the Clouds (e.g., Da Costa & Hatzidimitriou 1998; Pagel & Tautvaisiene 1998; Venn 1999; Piatti et al. 2001; Hill 2004; Cole et al. 2005; Carrera et al. 2008; Tsujimoto & Bekki 2009). One of intriguing observational results in terms of chemical abundances of the LMC is that star-forming HII regions and very young stellar populations in the LMC show apparently low [N/H] that is by a factor of $6-7$ lower than the solar value (e.g., Korn et al. 2002; Hill 2004; van Loon et al. 2010) while other elements such as O and Ne are underabundant by a factor of ~ 2 (Hill 2004). It remains observationally unclear whether only these young components in the LMC have such low [N/H] or other older ones also have it. It would be theoretically unlikely that all stellar populations and gas in the LMC have such low [N/H].

In any standard chemical evolution models, the N abundance will increase with time and reach the same level of enrichment as those of other elements in the reasonable scheme that stellar ejecta from asymptotic giant branch (AGB) stars (which are considered to be the major production site for N) in a galaxy is well recycled into and mixed with the ISM and subsequently the mixed gas is efficiently converted into new stars. Therefore the observed low [N/H] ~ -0.8 in HII regions and very young stellar populations of *the present* LMC with [Fe/H] ~ -0.3 appears to be at odds with theoretical predictions of previous chemical evolution models (e.g., Henry et al. 2000; Mollá et al. 2006). One of possible ways to solve this is to dilute the nitrogen abundance through recent infall of gas with low [N/H] onto the LMC based on the assumption that only young components in the LMC have such low [N/H]. There would be a number of possibilities for the gas resource, such as the Galactic HVCs, the SMC, and some gas-rich dwarfs orbiting the Galaxy.

The purpose of this paper is to discuss a new scenario in which the observed low [N/H] can be closely associated with the recent infall of the Galactic HVCs onto the LMC. Given that some HVCs presumably within the Galactic halo are observed to have low [N/H] ranging from -2.0 to -1.2 (Collins et al. 2007), the proposed scenario appears to be reasonable. In addition, the similarity of N/O ratio between the H II region ($\log(\mathrm{N/O}) \sim -1.5$) and the HVCs ($\log(\mathrm{N/O}) \sim -1.6$) implies some connection between them. Using an idealized model, we investigate how much accretion of the HVCs is necessary to dilute the star-forming ISM to the extent that [N/H] of new stars can have the observed low [N/H]. We then estimate the possible number and total mass of the Galactic HVCs for the required accretion rate of the HVCs. Given that previous numerical simulations demonstrated (i) the accretion of HVCs onto the Galaxy (e.g., Cameron & Torra 1994) and (ii) possible presence of a large number of HVCs in the Galactic halo (e.g., Peek et al. 2008), the HVCs can be accreted onto the

LMC if they collide with the LMC.

In the present paper, we do not intend to discuss why and how the HVCs have very low [N/H] (e.g., Collins et al. 2007), because this is simply beyond the scope of this paper. The origin of the low [N/H] would be closely associated with tidal stripping of outer HI gas of ancient gas-rich dwarfs, where chemical evolution did not proceed effectively (Bekki & Tsujimoto 2010, in preparation): our future papers will discuss why the stripped HI gas can have low [N/H] in detail. This paper thus focuses on (i) whether gas infall from the HVCs can explain the origin of the observed low [N/H] in the LMC and (ii) what other scenarios can explain it if the HVC infall scenario is not so plausible.

The Appendix in this paper shows the time evolution of [N/O] of stars in the LMC based on the standard one-zone chemical evolution model for the LMC and compares the simulated [N/O] of the present LMC with the observed one. The Appendix thus can help readers to understand (i) that this is a serious inconsistency between the theoretical prediction of [N/O] for the present stellar populations of the LMC and the corresponding observed one and thus (ii) that other factors need to be considered to reproduce the observed low nitrogen abundance of stars in the present LMC.

2. The required accretion rate of the Galactic HVCs

We here assume that (i) all of young stellar populations with ages less than $t_{\rm sf}$ have unusually low [N/H] in the LMC and (ii) the populations are formed exclusively from mixed gas of the original ISM of the LMC and the accreted gas (i.e., the Galactic HVCs). We adopt the above first assumption, because previous observations show no clear evidence for the presence of young stars and HII regions with normal [N/H] (e.g., Russell & Dopita 1990). The above second assumption means that the original ISM of the LMC has a "normal" [N/H] before external accretion of gas and thus needs to be diluted by the accreted gas to have low [N/H]. We discuss how the present results change if we relax these model assumption in §4.

We try to derive the total mass of the accreted HVCs ($M_{\rm HVC}$), for $t_{\rm sf}$, the observed present star formation rate of the LMC ($R_{\rm sf}$), the nitrogen abundance of the original ISM of the LMC ($A_{\rm g}$), that of the HVCs ($A_{\rm HVC}$), that of young population observed in the LMC ($A_{\rm obs}$), star formation efficiency for the mixed gas ($\epsilon_{\rm sf}$), and the total mass of the original ISM that can be converted into new stars ($M_{\rm g}$: therefore this is not the total mass of the entire ISM of the LMC, it is the local gas mass (initially in the LMC) mixing with the accreted HVCs to form new stars with low [N/H]). We assume that $t_{\rm sf}$ is constant during the formation of young stars (i.e., for $\sim 10^7$ yr in most models), because there is no/little

observational evidence which supports rapid change in star formation within an order of 10^7 yr: the periodic bursts of star formation are observationally suggested (e.g., Harris et al. 2009), but they are estimated for a time span of 100 Myr to several Gyrs.

We use the following two sets of equation to derive $M_{\rm HVC}$:

$$\epsilon_{\rm sf}(M_{\rm HVC}+M_{\rm g}) = t_{\rm sf}R_{\rm sf} \tag{1}$$

and

$$\frac{A_{\rm HVC}M_{\rm HVC}+A_{\rm g}M_{\rm g}}{M_{\rm HVC}+M_{\rm g}} = A_{\rm obs}. \tag{2}$$

For the above equation (1), we consider that (i) the star formation rate estimated from HII regions of the LMC ($\sim$ 0.26 $\rm M_{\odot}$ $\rm yr^{-1}$; Kennicutt et al. 1995) is reasonable in the present study and (ii) young stellar populations with ages less than $t_{\rm sf}$ were continuously formed with the star formation rate of $R_{\rm sf}$. We choose $A_{\rm obs}$ corresponding to the observed [N/H] (= -0.8) for HII regions and B-type of stars in the LMC (Korn et al. 2002). It is observationally unclear what the typical value of $A_{\rm HVC}$ is, though some observations show very low [N/H] ranging from -2.0 to -1.2 (Collins et al. 2007). Therefore we consider that $A_{\rm HVC}$ is a parameter with the above observed range. Since the present [Fe/H] of the LMC is observed to be -0.3 (e.g., van den Bergh 2000), we set the gaseous [N/H] to be -0.3 assuming [N/Fe]=0: we use $A_{\rm g}$ corresponding to this [N/H] value. We consider that $t_{\rm sf} \sim 10^7$ yr is reasonable, because the ages of stars (e.g., main-sequence B-type stars) observed for estimation of N abundances (Korn et al. 2002) correspond roughly to the above $t_{\rm sf}$. We however investigate models with different $t_{\rm sf}$

Fig. 1 shows how $M_{\rm HVC}$ required to decrease [N/H] of the ISM to ~ -0.8 depends on the nitrogen abundance of HVCs (denoted as $\rm [N/H]_{HVC}$) for $t_{\rm sf} = 10^7$yr in three models with different $\epsilon_{\rm sf}$. The required $M_{\rm HVC}$ ranges from $\sim 1.8 \times 10^6 \rm M_{\odot}$ to $\sim 2.2 \times 10^7 \rm M_{\odot}$ and is larger for smaller $\epsilon_{\rm sf}$ for a given $\rm [N/H]_{HVC}$ (i.e., $A_{\rm HVC}$). The reason for this is as follows: Only a smaller fraction of the accreted HVCs can be converted into new stars after mixing with the original ISM in the models with a smaller $\epsilon_{\rm sf}$. Therefore a larger amount of HVCs needs to be accreted to form the observed total mass of young stars with low [N/H]. The required $M_{\rm HVC}$ is larger for larger $\rm [N/H]_{HVC}$ for a given $\epsilon_{\rm sf}$. It should be stressed here that the derived $M_{\rm HVC}$ is for the ISM that forms young stars: it is not for the *entire* ISM of the LMC.

Fig. 1 also shows that the mass ratio of $M_{\rm HVC}$ to $M_{\rm g}$ is dependent on $\rm [N/H]_{HVC}$ in the sense that a larger amount of HVCs is necessary to lower the [N/H] of the ISM to the observed level for larger $\rm [N/H]_{HVC}$. The derived large mass-ratios $M_{\rm HVC}/M_{\rm g}$ (ranging from

~ 2.3 to ~ 5.8) mean that a significant degree of dilution of original ISM of the LMC by HVC infall is indispensable for explaining the observed low [N/H] in HII regions and young stars in the LMC. For example, the original gas of the LMC with $M_{\rm g} = 7.8 \times 10^5 {\rm M}_{\odot}$ is converted into new stars for $\epsilon = 1.0$ and $[{\rm N/H}]_{\rm HVC} = -2.0$ after being mixed with the HVCs with $M_{\rm HVC} = 1.8 \times 10^6 {\rm M}_{\odot}$. Fig. 2 shows that the required $M_{\rm HVC}$ is quite large ($\sim 6.3 \times 10^7 {\rm M}_{\odot}$) if young stars with ages less than 10^8yr uniformly have low [N/H] of -0.8. Fig. 2 also shows that the required $M_{\rm HVC}$ depends weakly on $[{\rm N/H}]_{\rm HVC}$ for a given $\epsilon_{\rm sf}$ in models with different $t_{\rm sf}$.

3. A possible total mass of the HVCs

Only a small fraction of the Galactic HVCs can interact with the LMC owing to the small disk size of the LMC. We here estimate (i) a typical timescale for the LMC to collide with one HVC ($t_{\rm col}$) for a given number density of the HVCs within the distance of the LMC from the Galactic center and (ii) an expected accretion rate of HVCs onto the LMC disk ($\dot{M}_{\rm HVC}$). Since we can estimate the accretion rate required for explaining the observed [N/H] using the results shown in Figs. 1 and 2 (i.e., $M_{\rm HVC}/t_{\rm sf}$), we can compare the expected and the required accretion rates and thereby assess the viability of the present scenario.

The time scale of a LMC-HVC collision event ($t_{\rm col}$) can be estimated as follows (e.g., Makino & Hut 1997);

$$t_{\rm col} = \frac{1}{n_{\rm HVC}\sigma v}, \tag{3}$$

where $n_{\rm HVC}$, σ, and v are the mean number density of the HVCs within the Galaxy, the geometrical cross section of the LMC, and a relative velocity between a HVC and the LMC. We here estimate $n_{\rm HVC}$ for the central 75 kpc of the Galaxy (corresponding roughly to the mean of the pericenter and apocenter distances of the LMC orbit; e.g., Bekki & Chiba 2005) and assume that $\sigma = \pi {R_{\rm LMC}}^2$, where $R_{\rm LMC}$ is the LMC size and v is velocity dispersion ($= v_{\rm c}/\sqrt(2)$, where $v_{\rm c}$ is the circular velocity thus 220 km s^{-1}) of the Galaxy halo. For convenience, we discuss $t_{\rm col}$ in terms of the total number of HVCs within 75 kpc from the Galaxy ($N_{\rm HVC}$) rather than $n_{\rm HVC}$ below. Previous observations found more than 600 HVCs (Wakker & van Woerden 1991) yet many initial HVCs have been already destroyed by tides and ram pressure (e.g., See Wakker 2004 for a review). Thus we consider that it is reasonable to investigate models with $N_{\rm HVC}$ ranging from a few hundreds to a few thousands.

Fig. 3 shows that $t_{\rm col}$ is shorter for larger $N_{\rm HVC}$ for a given $R_{\rm LMC}$ and shorter for larger $R_{\rm LMC}$ for a given $N_{\rm HVC}$. Fig. 3 also shows that $t_{\rm col}$ can be as low as $\sim 10^8$yr if the total number of the HVC within the LMC's orbit is as large as ~ 1000 for the size of the LMC

disk ($R_{\rm LMC} = 5$ kpc). It is clear from this Fig. 3 that if there are only a few hundreds HVCs within the LMC orbit, then the HVCs are highly unlikely to be accreted onto the LMC and consequently dilute the ISM within a timescale of well less than 10^8yr (which corresponds to ages of young stellar populations with low [N/H] in the LMC).

By assuming a typical mass of the individual HVCs ($m_{\rm hvc}$) and using the results shown in Fig. 3, we can discuss the possible accretion rate of the HVCs onto the LMC disk for a given set of model parameters. Fig. 4 shows that $\dot{M}_{\rm HVC}$ is much less than $\sim 0.1{\rm M}_{\odot}{\rm yr}^{-1}$ for almost all models with different $m_{\rm hvc}$ and $N_{\rm HVC}$. The minimum value of the required $M_{\rm HVC}$ shown in Fig. 1 is $1.8 \times 10^6{\rm M}_{\odot}$ for $t_{\rm sf} = 10^7$yr in different models with different $\epsilon_{\rm sf}$ and $[{\rm N/H}]_{\rm HVC}$. Therefore, at least 0.18 $\rm M_{\odot}$ yr^{-1} is necessary to dilute the ISM of the LMC to the observed level for $t_{\rm sf} = 10^7$ yr. It should be stressed that the above 0.18 $\rm M_{\odot}$ yr^{-1} is for $\epsilon_{\rm sf} = 1.0$ (i.e., 100% star formation efficiency): a realistic value of the required $\dot{M}_{\rm HVC}$ is likely to be significantly larger than 0.18 $\rm M_{\odot}$ yr^{-1}.

The results shown in Fig. 4 suggest that only models with very large typical masses of HVCs (i.e., $m_{\rm hvc} = 10^7{\rm M}_{\odot}$) and large number of the HVCs ($N_{\rm HVC} > 2500$) can show $\dot{M}_{\rm HVC}$ as high as the required rate above (0.18 $\rm M_{\odot}$ yr^{-1}). Although the required typical mass is similar to the observed mass of Complex C (e.g., Thom et al. 2008), the required total number within the LMC's orbital radius already exceeds the total number of the HVCs (~ 2000) observed by the HI Parkes All Sky Survey (HIPASS; e.g., Putman et al. 2002): it should be noted that the observed one is for the HVCs existing in the entire regions around the Galaxy whereas the required one is only for those within ~ 75 kpc. These results imply that it is unlikely for the accretion of the Galactic HVCs onto the LMC disk to dilute the ISM. However $\dot{M}_{\rm HVC}$ could become large enough in a sporadic way if the LMC can interact with groups of HVCs with locally large number densities.

4. Discussion

4.1. On model uncertainties

Although we have adopted a reasonable range of model parameters and thereby investigated (i) the accretion rate of the HVCs onto the LMC and (ii) the possible total mass of the HVCs within the outer Galactic halo, there could be some uncertainties in model parameters. Thus we here discuss how the present results depend on these model parameters.

4.1.1. *The required accretion rate of the HVCs*

We assumed that (i) all of young stellar populations with ages less than $t_{\rm sf}$ have unusually low [N/H] in the LMC and (ii) the populations are formed exclusively from mixed gas of the original ISM of the LMC and the accreted gas. If we relax the first assumption, then $M_{\rm HVC}$ required for explaining the observed low [N/H] in the LMC can change significantly. In the following discussion, we define $f_{\rm sf}$ as a fraction of stars having unusually low [N/H] among all stars formed during $t_{\rm sf}$ for convenience. For example, if only 10% (i.e., $f_{\rm sf} = 0.1$) of the young populations with $t_{\rm sf} \leq 10^7$ yr can show low [N/H] in models with $\epsilon_{\rm sf} = 0.3$, then the required $M_{\rm HVC}$ can be by a factor of 10 smaller than those derived in models (with $\epsilon_{\rm sf} = 0.3$) shown in Fig. 1: the required $M_{\rm HVC}$ can be derived from the equations (1) and (2) by replacing $t_{\rm sf}R_{\rm sf}$ by $f_{\rm sf}t_{\rm sf}R_{\rm sf}$.

Given the two equations (1) and (2), the required $M_{\rm HVC}$ is smaller for smaller $f_{\rm sf}$. This means that a smaller number of HVCs need to be accreted by the LMC so that the observed unusually low [N/H] can be explained by the HVC accretion/collision scenario. This furthermore means that a smaller number of HVCs need to exist in the outer Galactic halo for a given typical mass of the HVCs (see discussion in §3). However, young stellar populations are observed to have a low dispersion in [N/H] (e.g., Russel & Dopita 1990): it is highly unlikely that a significant fraction of young stellar populations have normal [N/H] (i.e., $f_{\rm sf}$ can be close to 1, as adopted in §2.).

If we relax the second assumption (i.e., only some fraction of the HVC can be mixed into the ISM of the LMC), then the required $M_{\rm HVC}$ can also change. In the following discussion, we define $f_{\rm HVC}$ as a mass fraction of HVCs that can be mixed into ISM and then converted into new stars for convenience. Given the equations (1) and (2), the required $M_{\rm HVC}$ can be larger for smaller $f_{\rm HVC}$ (the required $M_{\rm HVC}$ is inversely proportional to $f_{\rm HVC}$). This means that a larger number of the Galactic HVCs need to exist in the outer Galactic halo for smaller $f_{\rm HVC}$. We adopted $f_{\rm HVC} = 1$ in §2 and 3 and showed that the required number of the HVCs appears to be already too large. Thus the HVC accretion/collision scenario becomes less viable if we adopt smaller $f_{\rm HVC}$: the main conclusion that the HVC scenario is unlikely (as described later) does not depend on $f_{\rm HVC}$.

4.1.2. *The possible total mass of the HVCs*

Even if our estimation of the required $M_{\rm HVC}$ is reasonable, there could be some model uncertainties in estimating the total mass of the HVCs in the outer Galactic halo and the possible accretion rate of the HVCs onto the LMC. Given the equation (3), $t_{\rm col}$ (thus $\dot{M}_{\rm HVC}$)

can change if we adopt different v_c. For example, t_{col} is by a factor of 0.88 smaller if we adopt $v_c = 250$ km s^{-1} that has been recently suggested by observations (e.g., Uemura et al. 2000). This means that $\dot{M}_{\rm HVC}$ can be by a factor of 1.1 larger in models with $v_c = 250$ km s^{-1} than those in models with $v_c = 220$ km s^{-1} (shown in Fig. 4). This very small change of $\dot{M}_{\rm HVC}$ due to possibly different v_c suggests that the present results on $\dot{M}_{\rm HVC}$ can be reasonable.

It should be stressed here that the uniform distribution of the HVCs within the Galactic halo is assumed in the present estimation. Therefore, it would be possible for $\dot{M}_{\rm HVC}$ to become large enough in a sporadic way if the LMC can interact with groups of HVCs with locally large number densities. It is however very hard to estimate this effect of sporadic accretion in a quantitatively way owing to lack of observational results on the 3D distribution of the Galactic HVCs. Therefore we can just say that $\dot{M}_{\rm HVC}$ depends on the 3D spatial distribution of the HVCs within the Galactic halo and thus that the present study can underestimate $\dot{M}_{\rm HVC}$ significantly.

4.1.3. Delayed star formation after gas infall ?

We have so far assumed that star formation can occur immediately after the collision/accretion of the Galactic HVCs onto the LMC's gas disk. Owing to this assumption, a larger amount of HVCs needs to be accreted within a relatively short time-scale ($\sim 10^7$ yr). However, if star formation events due to the HVC collision/accretion can be well (e.g., $\sim 10^8$ yr) after the HVC accretion events (and if only the very young stars have unusually low [N/H], as assumed in the present paper), then the required rate of the HVC accretion can become significantly lower: the required total mass of the accreting HVCs is the same, but the HVCs can be accreted within a longer time scale so that the net accretion rate can be significantly lower.

Given that $\sim 10^8$ yr corresponds to one rotation period of the LMC for a reasonable set of dynamical parameters of the LMC (e.g., Bekki & Chiba 2005), *global mixing* of the ISM and infalling gas due to kpc-scale dynamical processes (e.g., dynamical action of the stellar bar) can happen within $\sim 10^8$ yr. This means that the proposed delayed star formation would be promising only if the accreted HVCs do not *globally* mix with the almost entire ISM with normal [N/H] for a such long timescale of $\sim 10^8$ yr, because such global chemical mixing will result in larger [N/H] of stars formed well after the HVC accretion events owing to the much larger total mass of the ISM.

4.2. Infall from the SMC rather than from the HVCs ?

We adopted an assumption that only very young stellar populations formed from mixed gas of HVCs and ISM in the LMC have unusually low [N/H] in the LMC: the accretion events of HVCs onto the LMC need to happen only recently. We have shown that the large number (> 2500) of massive HVCs ($\sim 10^7 \mathrm{M}_\odot$) are required to exist within the LMC's orbital radius with respect to the Galactic center: the required total mass of HVCs ($M_{\mathrm{HVC,G}}$) in the Galactic halo is about $\sim 2.5 \times 10^{10} \mathrm{M}_\odot$ for a reasonable set of model parameters. Although the previous numerical simulations tried to predict the total mass of the Galactic HVCs, the predicted mass ranges widely from $\sim 10^8 \mathrm{M}_\odot$ (Peek et al. 2008) to $\sim 2 \times 10^{10} \mathrm{M}_\odot$ (Maller & Bullock 2004). The required $M_{\mathrm{HVC,G}}$ to explain the observed low [N/H] in the present scenario appears to exceed the predicted $M_{\mathrm{HVC,G}}$.

Given that the typical mass and 3D distribution of the Galactic HVCs remains observationally unclear (e.g. Wakker 2004), the above inconsistency between the required total mass of HVCs and the theoretically predicted one does not rule out the present scenario. It is, however, reasonable that gas from other sources (e.g., galaxies in the Local Group) can also play a role in diluting the ISM of the LMC. Recently, Bekki & Chiba (2007) have shown that the ISM stripped from the SMC during the LMC-SMC-Galaxy interaction for the past 2 Gyr can collide with the LMC's disk around 0.2 Gyr ago. We thus suggest the following "SMC-transfer" scenario (or "Magellanic squall"; Bekki & Chiba 2007). During the last 0.2 Gyr, the LMC and the SMC have interacted each other like a binary through their strong gravitational fields. As a result of this tidal interaction, gas with low [N/H] in the SMC can be transferred efficiently to the LMC sporadically, which induces star formation and thus creation of HII regions with low [N/H] in the LMC. Thus the observed low [N/H] of young populations in the LMC is a result of a close tidal interaction between MCs in the last 0.2 Gyr or so.

We here suggest that this SMC-transfer scenario has the following three advantages in explaining the observed low [N/H]. Firstly, the relative velocities between the infalling gas from the SMC and the LMC's gas disk can be as small as ~ 60 km s^{-1}, because the relative velocity between the LMC and the SMC is ~ 60 km s^{-1} for the last 200 Myrs (e.g., orbital models of the LMC and the SMC shown in Bekki & Chiba 2005). The relative velocity is significantly smaller than the circular velocities of the LMC ($\sim 80 - 120$ km s^{-1} for a reasonable mass model of the LMC; Bekki & Chiba 2005) so that the infalling gas is highly likely to be trapped by the gravitational potential of the LMC. On the other hand, the relative velocities of the HVCs and the LMC can be as large as the velocity dispersion of the Galactic halo (~ 160 km s^{-1}) so that the infalling HVCs are less likely to be trapped by the LMC in comparison with the infalling SMC gas.

Secondly Bekki & Chiba (2007) have shown that about 18% of the gas within the SMC can pass through the LMC about 0.2 Gyr ago. If the SMC's initial gas mass before gas stripping is $\sim 10^9 M_\odot$, then a significant amount of gas (as much as $\sim 10^8 M_\odot$) can be accreted onto the LMC. This is much larger than the total amount of HVCs that can be accreted onto the LMC for the last $\sim 10^7$ yr, as shown in the previous sections. Furthermore, the accretion event of a large amount of gas from the SMC can occur when the SMC approaches the LMC very closely so that the accreted gas can *simultaneously* trigger star formation in the LMC: most HII region can show systematically low [N/H]. Possibly sporadic accretion of HVCs would be unlikely to cause such synchronized star formation in the LMC.

Thirdly, Bekki & Chiba (2007) have already shown that the gas-transfer between the LMC and the SMC is possible for the last 200 Myrs using the results of numerical simulations. However, no one has demonstrated that the massive HVCs like Complex C with physical sizes of 10 kpc $\times$ 10 kpc (e.g., Wakker et al. 1999) can be really accreted onto the LMC owing to hydrodynamical interaction between the LMC's gas disk and the HVCs in spite of the large relative velocities (~ 160 km s^{-1}) between them. If only some minor fractions (e.g., 10%) of the HVC masses can be accreted onto the LMC during HVC-LMC collisions, then the required number of the Galactic HVCs for explaining the observed [N/H] in the LMC can be unrealistically large.

Thus, if the ISM of the SMC has rather low [N/H] and if the stripped gas can be mixed into the ISM of the LMC and then converted into new stars, the newly formed stars can show low [N/H]. Indeed the HII regions and young stellar populations of the SMC are observed to have [N/H] by a factor of ~ 18 lower than the solar value (e.g., Pilyugin et al. 2003; Rolleston et al. 2003; Hill 2004), which implies that the ISM of the SMC could possibly have low [N/H] (though the low [N/H] could be only for the young stellar populations, not for the entire ISM). The required gas corresponding to this [N/H] is $\sim 10^6 - 10^7 M_\odot$ (see Fig.1). Thus, the predicted amount of gas transferred from the SMC to the LMC of $\sim 10^8 M_\odot$ (Bekki & Chiba 2007) is sufficient to dilute the N abundance in the LMC as observed.

However, the SMC-transfer scenario has some disadvantages in explaining clearly the observed low [N/H] both in the LMC and the SMC. For example, if the origin of the unusually low [N/H] in the LMC is due to the gas transfer between the Clouds, then the next question is as to why the SMC has ISM with such low [N/H]: this point is yet to be answered by the SMC-transfer scenario. Previous chemical evolution models did not clearly show that the present-day dwarf galaxies like the SMC can have very low [N/H] (e.g., Henry et al. 2000; Mollá et al. 2006): the Appendix also implies that canonical chemical evolution models can hardly show very low [N/H] in the present stellar populations for Magellanic-type dwarf galaxies. We need to discuss why the ISM of the SMC can have low [N/H] in our future

paper (Bekki & Tsujimoto 2010).

Also, the gas infall of such low-metallicity gas (with a possibly large mass of $\sim 10^8 M_\odot$) from the SMC would lower [Fe/H] of the LMC significantly: although the presence of metal-poor young clusters (e.g., NGC 1984 with an age of $\sim$ 4 Myr and [Fe/H]~ -0.9; Santos & Piatti 2004) would suggest a possible evidence of dilution of ISM by low-metallicity gas, there are no observational results which suggest that the young stellar populations as a whole show such low [Fe/H] in the LMC (It should be noted here that this problem may be true for the HVC scenario). Furthermore, the gas accretion from the SMC to the LMC can occur most efficiently about 0.2 Gyr ago (Bekki & Chiba 2007). This means that the SMC-infall scenario needs to explain how the gas infall can still continue to occur until quite recently (until only 10 Myrs ago) so that the very young populations of the LMC can be formed with low [N/H] from the accreted gas.

The HVC infall scenario suggests that if the HVCs can be accreted onto the LMC, then they can be accreted also onto the SMC owing to the similar locations and velocities between the LMC and the SMC with respect to the Galactic center. Therefore, it can naturally explain why both the LMC and the SMC show low [N/H] in their young stellar populations. As pointed out above, both the HVC infall scenario and the SMC-transfer one have advantages and disadvantages in explaining the observed chemical properties of the LMC and the SMC. Thus it would be reasonable for us to say that both scenario are possible at present.

4.3. A possible observational evidence for external gas infall onto the LMC

If chemical evolution of the LMC is influenced by accretion of gas from outside the LMC (e.g., from the Galactic halo or other gas-rich galaxies), then the chemical evolution strongly depends on the orbital evolution of the LMC. The LMC may have obtained steadily gas from the accretion events of the Galactic HVCs for at least $3-4$ Gyr for the "classical bound orbit" adopted in previous dynamical models for the evolution of the LMC (e.g., Bekki & Chiba 2005). For this classical orbital model, the LMC can show lower [N/H] not only in young stellar populations but also in intermediate-age ones, if the dilution by the continuous gas infall has been overwhelming over chemical enrichment by the AGB stars continuously formed in the LMC for the last 3-4 Gyr. If the LMC has just recently arrived in the Galaxy, as the latest proper motion studies by *HST* (Kallivayalil et al. 2006) has suggested, then the LMC may have started the accretion of the HVCs quite recently (well less than $\sim$ 1 Gyr): the low [N/H] can be seen only in young stellar populations.

We have so far considered that all of young stellar populations in the LMC have unusually low [N/H] and were formed from *mixed gas* of the LMC's ISM and the accreted gas from outside. However, some local regions where accretion of gas with very low [N/H] does not occur may well form young stellar populations with normal [N/H]. In this case, the young populations in the LMC may well show a large dispersion in [N/H] in the present scenario. The previous observations on the chemical abundances for HII regions of the LMC indeed shows a dispersion in [N/H] (e.g., Russell & Dopita 1990), though the dispersion appears to be smaller (see Fig. 5). If future observations confirm that the dispersion in [N/H] is really small in the LMC (i.e., [N/H] is uniformly low for the entire young populations), then it means that young populations in the LMC were formed exclusively from mixed gas of the original ISM of the LMC and the accreted gas for some physical mechanisms.

However, it should be stressed that if the *entire ISM* (i.e., not only cold HI and molecular gas but also HII regions) of the present LMC has unusually low [N/H] for some physical reasons, no accretion event of gas outside the LMC is required for explaining the origin of the observed young stellar populations with unusually low [N/H]: both old and young stellar populations have unusually low [N/H]. If this is the case, then the next question is why and how the [N/H] of the ISM in the LMC has continued to be very low until the mean metallicity of the LMC has become as high as [Fe/H]~ -0.3. No previous chemical evolution models appear to have shown very low [N/H] in *the present* galaxies with lower mean metallicities like the LMC (e.g., Mollá et al. 2006). This implies that it is unlikely that the entire ISM of the LMC has very low [N/H]: it is natural to consider that external gaseous accretion has recently changed [N/H] in the ISM with originally normal [N/H] (see the Appendix on this issue).

Then, is there any possible observational evidence for recent accretion events of gas in the LMC? In order to answer this question, we have investigated the dependences of log(N/O) on 12+log(O/H) for the HII regions of the LMC using already existing data sets (Peimbert & Torres-Peimbert 1974; Dufour 1975; Pagel et al. 1978; Russell & Dopita 1990; Simpson et al. 1995). Fig. 5 shows that (i) there is no clear correlation between log(N/O) and 12+log(O/H) and (ii) HII regions with larger 12+log(O/H) do not show larger log(N/O). These are inconsistent with previous chemical evolution models (e.g., Henry et al. 2000) demonstrating that stars and gas with larger 12+log(O/H) have larger log(N/O): It should be noted here that infall of gas with low [N/H] are not included in the models. We thus suggest that the observed lack of HII regions with larger 12+log(O/H) and larger log(N/O) are due to accretion of gas with low [N/H]: original HII regions with larger log(N/O) and larger 12+log(O/H) can disappear owing to the dilution of [N/H] caused by the gaseous accretion.

4.4. Observational implications: effects on other elements

Recent gas infall should also influence abundances of young population in the LMC for the elements other than N. Here we discuss this issue by comparing the LMC abundance with those of HVCs or the SMC. Supergiants in both the LMC and the SMC basically exhibit the solar abundance ratios for α-elements and iron-peak elements (Hill 2004). In addition, both MCs exhibit a similar overabundance for neutron-capture elements (Hill 2004). In this way, two galaxies have a very similar present-day elemental abundance pattern. It implies that gas infall from the SMC would dilute the N abundance with little imprint in other elemental ratios.

On the other hand, the information on abundances of HVCs for the elements other than N and O is very restricted. Complex C seems to exhibit an essentially solar pattern for α-elements (O, S, Si) in comparison with Fe but with a possible slightly-enhanced [α-elements/Fe] (Collins et al. 2007). If the future observation reveals the clear SN II-like [α-elements/Fe] for HVCs, we will be able to conclude that the dilution by them will change the LMC abundance into the one at odds with the observed LMC abundance. However, at the moment, it can be said that large impact on abundances by infall of HVCs is likely to be seen only in the deficiency of the N abundance.

4.5. Other possible scenarios

The proposed accretion scenario in the present paper might well be one of possible scenarios. Whatever alternative scenario is proposed, it would need to discuss the origin of the unusually low [N/H] in the context of an unique LMC's environment (e.g., interaction with the Galaxy and the SMC). We here discuss three alternative scenarios that could possibly explain the observed unusually low [N/H]. The first is that the stellar winds of AGB stars (i.e., rich sources of nitrogen) can be efficiently and continuously stripped from the LMC owing to hydrodynamical interaction between the LMC and the Galactic warm halo gas so that the present [N/H] can be rather low. This scenario with selective loss of AGB ejecta would have a problem of explaining other observational results on chemical abundances of stars (e.g., the observed abundances of s-process elements).

However, it is possible that stellar ejecta only from massive AGB stars (i.e., rich source of nitrogen) are removed owing to the stronger winds whereas those from low-mass ones (i.e., rich sources of s-process elements) are not. If this is the case, the above problem associated with the s-process elements would not be so serious for the selective loss scenario. We consider that this scenario is highly unlikely, because it needs to explain why gas from supernovae

(which are more energetic) can be kept within the LMC: recycling of the supernovae ejecta is inevitable to reproduce the chemical feature of the LMC.

The second is that the initial mass function (IMF) is different in the LMC in the sense that a much smaller number of stars (i.e., massive AGB stars) mainly contributing to the production of nitrogen can be formed in the history of the LMC. This idea confronts the same problem as the first one. The LMC requires the IMF that keeps the number of both low-mass AGB stars and massive ($> 10\mathrm{M}_{\odot}$) stars while reduces the number of stars residing in the middle of them. It is hard to formalize such an IMF. The third one is that nitrogen production in AGB stars is significantly suppressed in the LMC at least for the last few Gyr. Indeed, the observed level of N enrichment in the solar neighborhood can not be realized without introducing the metallicity-dependent N yield, which is also predicted by theoretical studies on nucleosynthesis in AGB stars (e.g., Ventura et al. 2002). Therefore, if the N yield did not depend on the metallicity, the present-day N abundance would become significantly smaller as observed in the LMC. Evidently, there is no physical reason for making such difference between the LMC and the Galaxy.

Thus, the three alternative scenarios are much less convincing in comparison with the present one in which the dilution of ISM by gas infall is responsible for the observed low [N/H] in young stellar populations of the LMC, though we did not quantitatively investigate the evolution of nitrogen abundances in stars and ISM of the LMC using chemical evolution models with the proposed unusual IMFs. The required gas with low [N/H] is less likely to come from the Galactic HVC, though the HVC infall scenario can not be ruled out currently. The gas accretion from the SMC is a possible scenario, which however has both advantages and disadvantages in explaining the observations. We suggest that the observed unusually low [N/H] in the LMC seems to tell us something about the unique chemical evolution history coupled with the past dynamical evolution.

5. Conclusion

Given that the observed unusually low [N/H] in young populations of the LMC can not be simply reproduced by canonical chemical evolution models for the LMC, we have investigated a new scenario in which the observed low [N/H] can be closely associated with recent collision and subsequent accretion of HVCs that surround the Galaxy and have low nitrogen abundances. We have shown that even if the observed low [N/H] is limited to very young stars with ages less than $\sim 10^7$ yr, the collision/accretion rate of the HVCs onto the LMC needs to be $\sim 0.2\mathrm{M}_{\odot}\ \mathrm{yr}^{-1}$ (corresponding to the total HVC mass of $10^6 - 10^7\mathrm{M}_{\odot}$) to dilute the original interstellar medium (ISM) before star formation.

We have demonstrated that if the typical mass of HVCs accreted onto the LMC is $\sim 10^7 M_{\odot}$, the Galaxy needs to have ~ 2500 massive HVCs within the LMC's orbital radius with respect to the Galactic center in order to explain the required accretion rate of the HVCs. Although we have adopted a number of model assumptions in deriving the required number of the HVCs, the required number of massive HVCs suggests that the HVC infall scenario is possible yet unlikely to efficiently dilute the ISM of the LMC and consequently lower the [N/H]. We thus have discussed the alternative SMC-transfer scenario in which the transfer of gas with low [N/H] from the SMC to the LMC can explain the observed low [N/H].

The SMC-transfer scenario has some advantages in explaining the observations (e.g., a higher probability of an enough amount of gas to be accreted onto the LMC) over the HVC infall one. However it also appears to have some problems in explaining self-consistently the observed chemical properties of the LMC. For example, it is not so clear in the SMC-transfer scenario why the gas accretion can continue to occur until quite recently. We thus conclude that although the observed low [N/H] of young populations in the LMC has an external origin (i.e., gas infall from outside the LMC), the host objects which the external gas originates from are yet to be determined.

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6. The Appendix

We consider that it is useful to show how the nitrogen abundance in the LMC evolves with time in a reasonable one-zone chemical evolution model of the LMC, because no theoretical works have yet clearly demonstrated that canonical chemical evolution models can not reproduce the observed low [N/H] in the LMC. We here discuss whether the observed [N/O] in the LMC can be reproduced by a canonical one-zone chemical evolution model which is consistent with the observed age-metallicity relation of stellar population in the LMC. Here we assume the standard Salpeter IMF. Details of model description is presented in Tsujimoto & Bekki (2010), including the chemical yields from stars with different masses. We will discuss time evolution of [N/H] in different galaxies with different physical properties using these models in our future papers.

Fig. 6 shows both the time evolution of [Fe/H] and [N/O] for the last ~ 13.5 Gyr and the observed values so that we can clearly see how serious the observed low nitrogen abundance is in the standard chemical evolution models with no external infall of gas. As shown in Fig. 6, [N/O] can be low in the early stage of the LMC evolution when log(N/O)+12 was lower than 8 (when the LMC was much younger). However it is clear that log(N/O) (~ -1.1) in the present LMC (at log(O/H)+12~ 8.4) for the standard chemical evolution model is much larger than the observed one (~ -1.5). This result demonstrates that some additional factors such as unique IMFs and external gaseous infall from outside of the LMC need to be considered in order to reproduce the observed low [N/O] in the LMC. We suggest that HVCs and gaseous components of the SMC can be the promising candidates for the external infall of gas.

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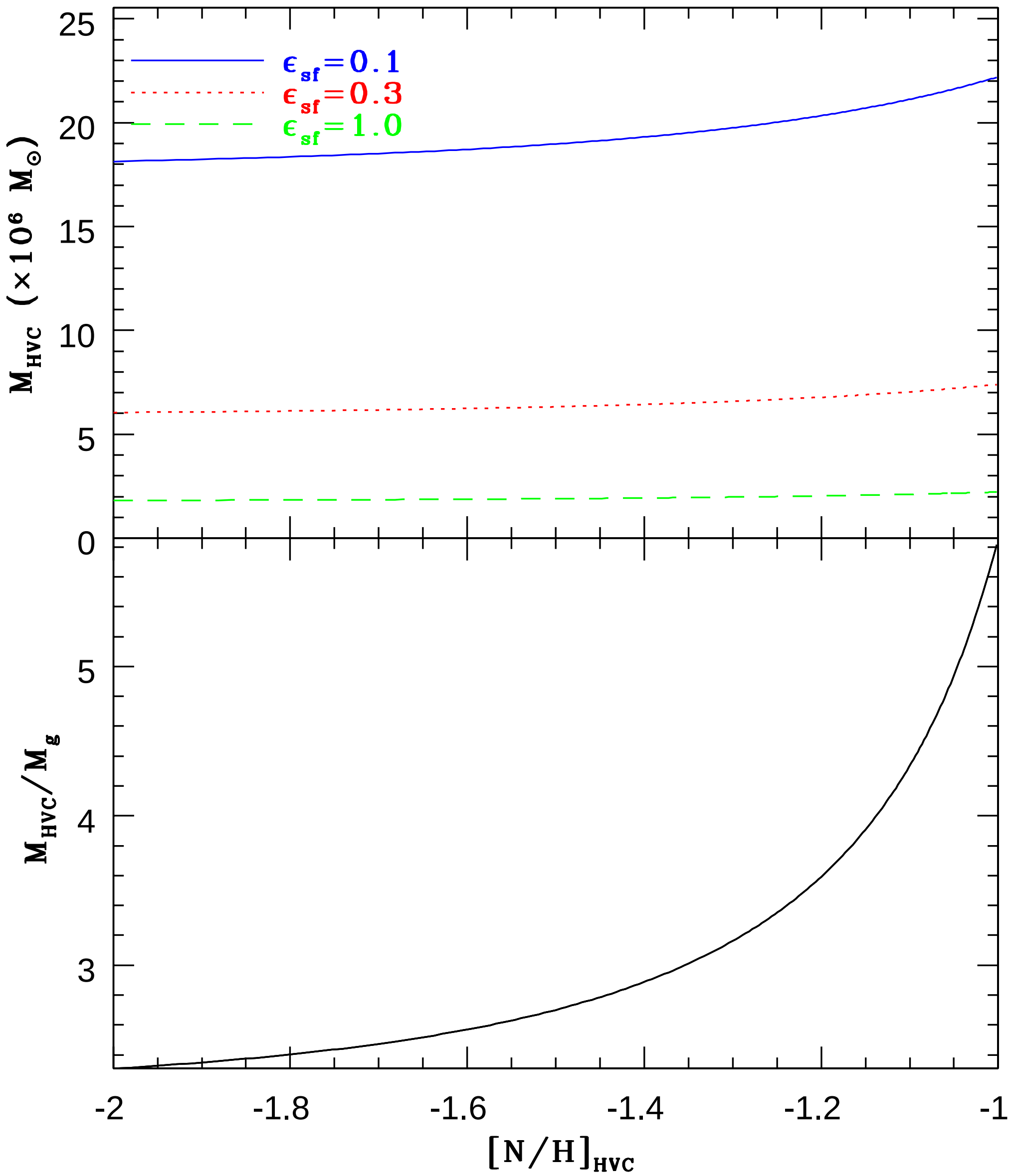

Fig. 1.— The dependences of $M_{\rm HVC}$ (upper) and the mass ratio of $M_{\rm HVC}$ to $M_{\rm g}$ (lower) on the nitrogen abundances of the HVCs ($[{\rm N/H}]_{\rm HVC}$) for three different models with $\epsilon_{\rm sf}$ = 0.1 (blue, solid) $\epsilon_{\rm sf}$ = 0.3 (red, dotted) and $\epsilon_{\rm sf}$ = 1.0 (green, dashed) for a fixed $t_{\rm sf}$ (=10^7 yr). Here $M_{\rm HVC}$ is the total mass of the Galactic HVCs required to explain the observations and $M_{\rm g}$ is the total mass of the LMC ISM that can mix with the HVCs to form new stars. The mass ratio $M_{\rm HVC}/M_{\rm g}$ does not depend on $\epsilon_{\rm sf}$ so that only a line (black, solid) is shown in the lower panel. It is clear that a larger amount of HVCs is necessary to dilute the ISM of the LMC to the observed level for smaller $\epsilon_{\rm sf}$.

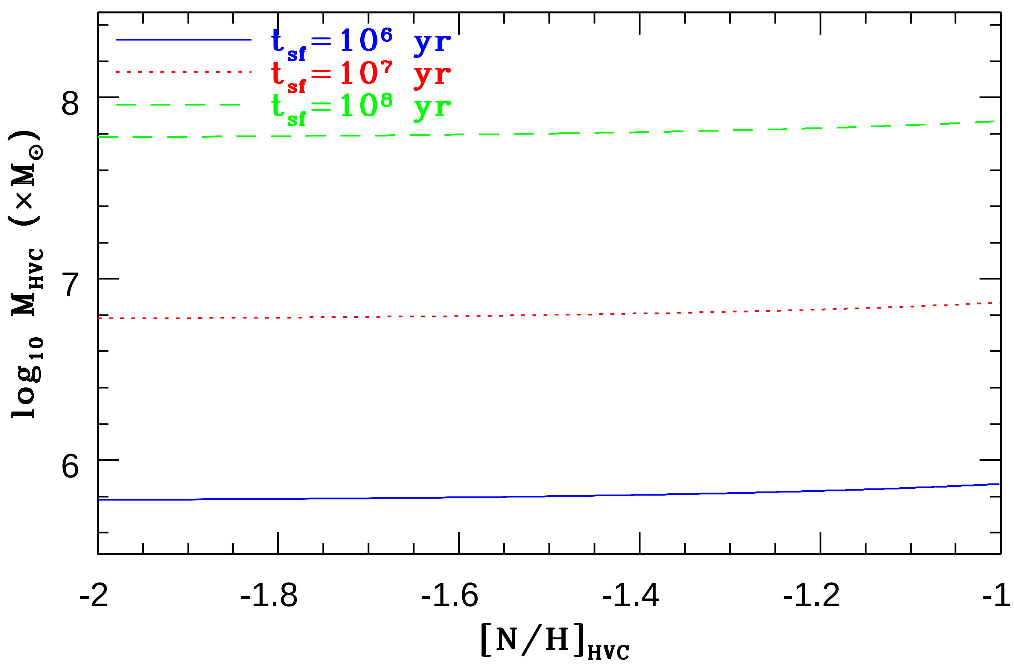

Fig. 2.— The dependences of $M_{\rm HVC}$ (in logarithmic scale) on $[{\rm N/H}]_{\rm HVC}$ for models with $t_{\rm sf} = 10^6$ yr (blue, solid), 10^7 yr (red, dotted), and 10^8 yr (green dashed) for a fixed $\epsilon_{\rm sf}$ (=0.3).

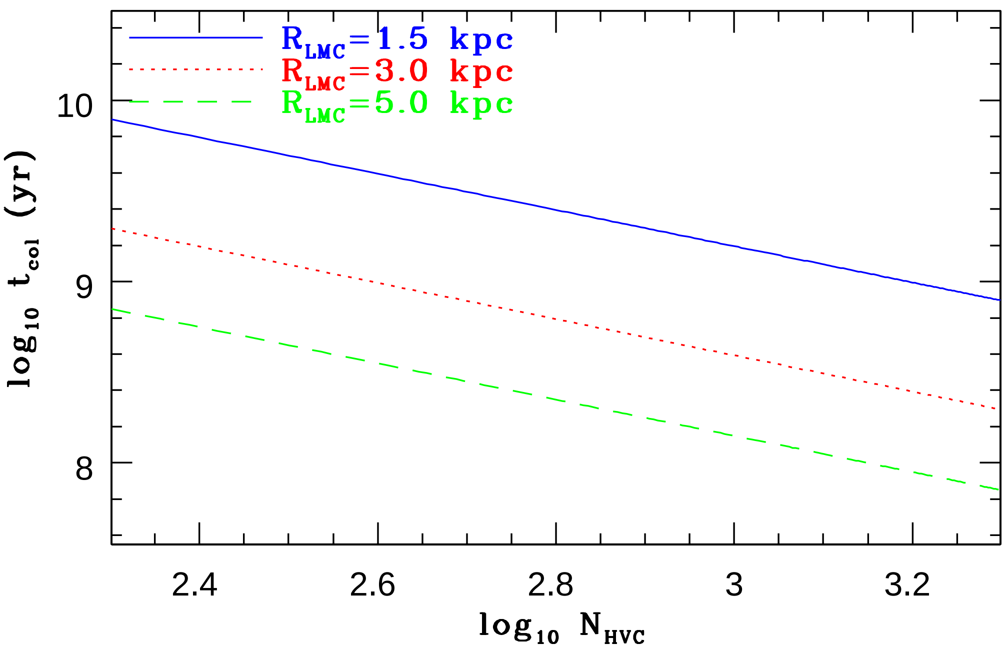

Fig. 3.— The dependences of $t_{\rm col}$ (the timescale of the LMC to collide a HVC in the Galactic halo) on $N_{\rm HVC}$ (the total number of the HVCs) for models with $R_{\rm LMC} = 1.5$ kpc (blue, solid), 3.0 kpc (red, dashed), and 5.0 kpc (green, dashed).

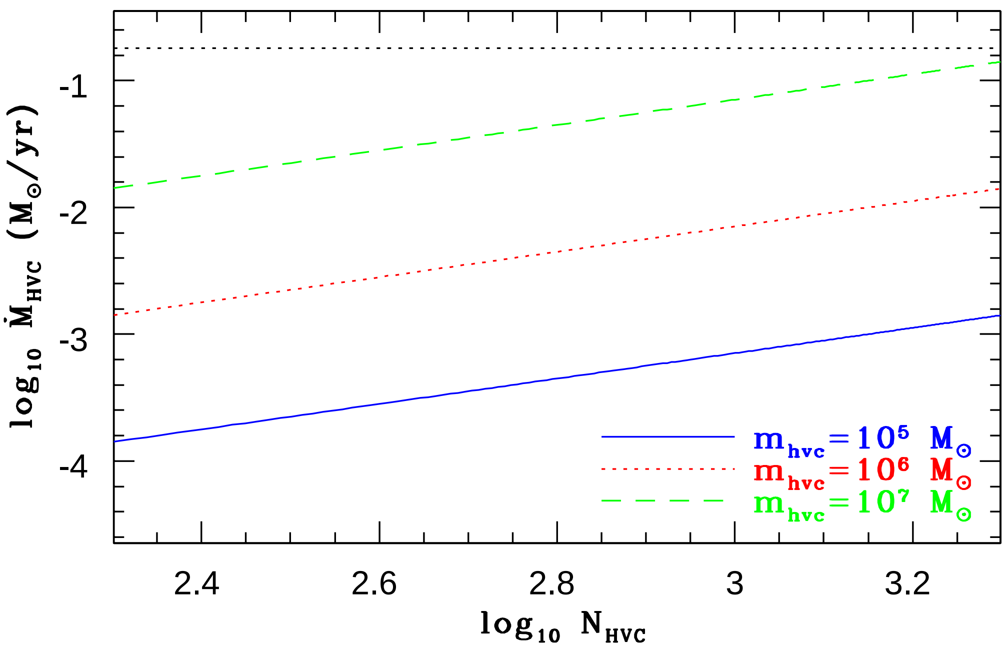

Fig. 4.— The dependences of $\dot{M}_{\rm HVC}$ (the accretion rate of the HVCs onto the LMC) on $N_{\rm HVC}$ (the total number of the HVCs) for models with $m_{\rm hvc}$ (the typical mass of individual HVCs) of $10^5{\rm M}_{\odot}$ (blue, solid), $10^6{\rm M}_{\odot}$ (red, dotted), and $10^7{\rm M}_{\odot}$ (green dashed). A horizontal black dotted line indicates the minimum value of $M_{\rm HVC}$ for models with $t_{\rm sf} = 10^7$ yr shown in Fig. 1. Note that $\dot{M}_{\rm HVC}$ can not be as high as the required $M_{\rm HVC}$ in all three models for the adopted range of $N_{\rm HVC}$.

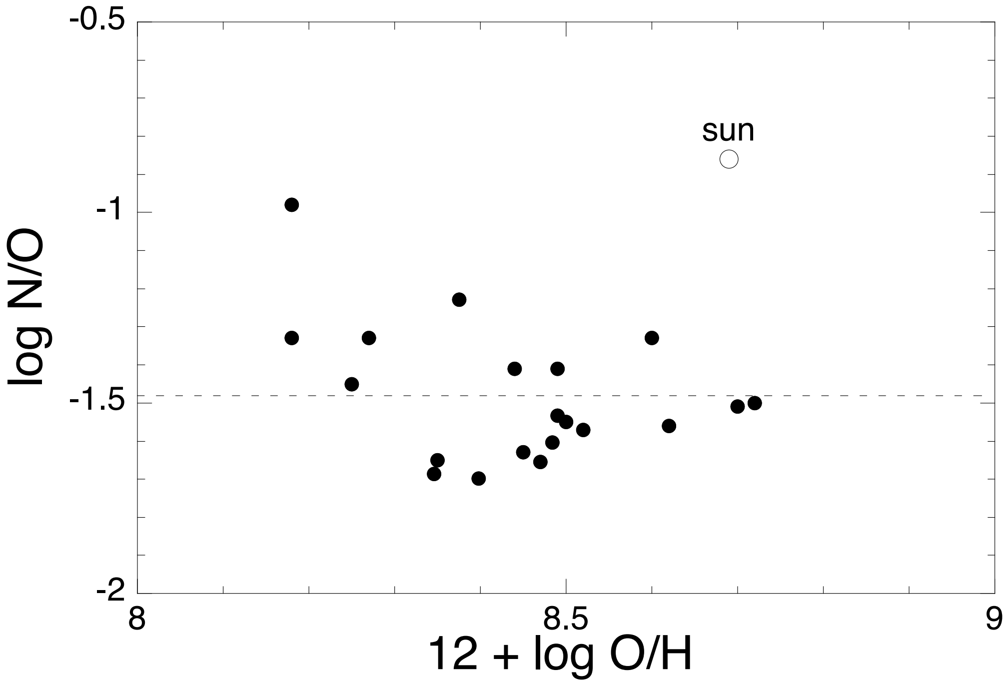

Fig. 5.— The observed dependence of logN/O on 12+logO/H for the HII regions of the LMC. For comparison, the result for the Sun is shown. A dotted line indicates the mean of the observed HII regions in the LMC.

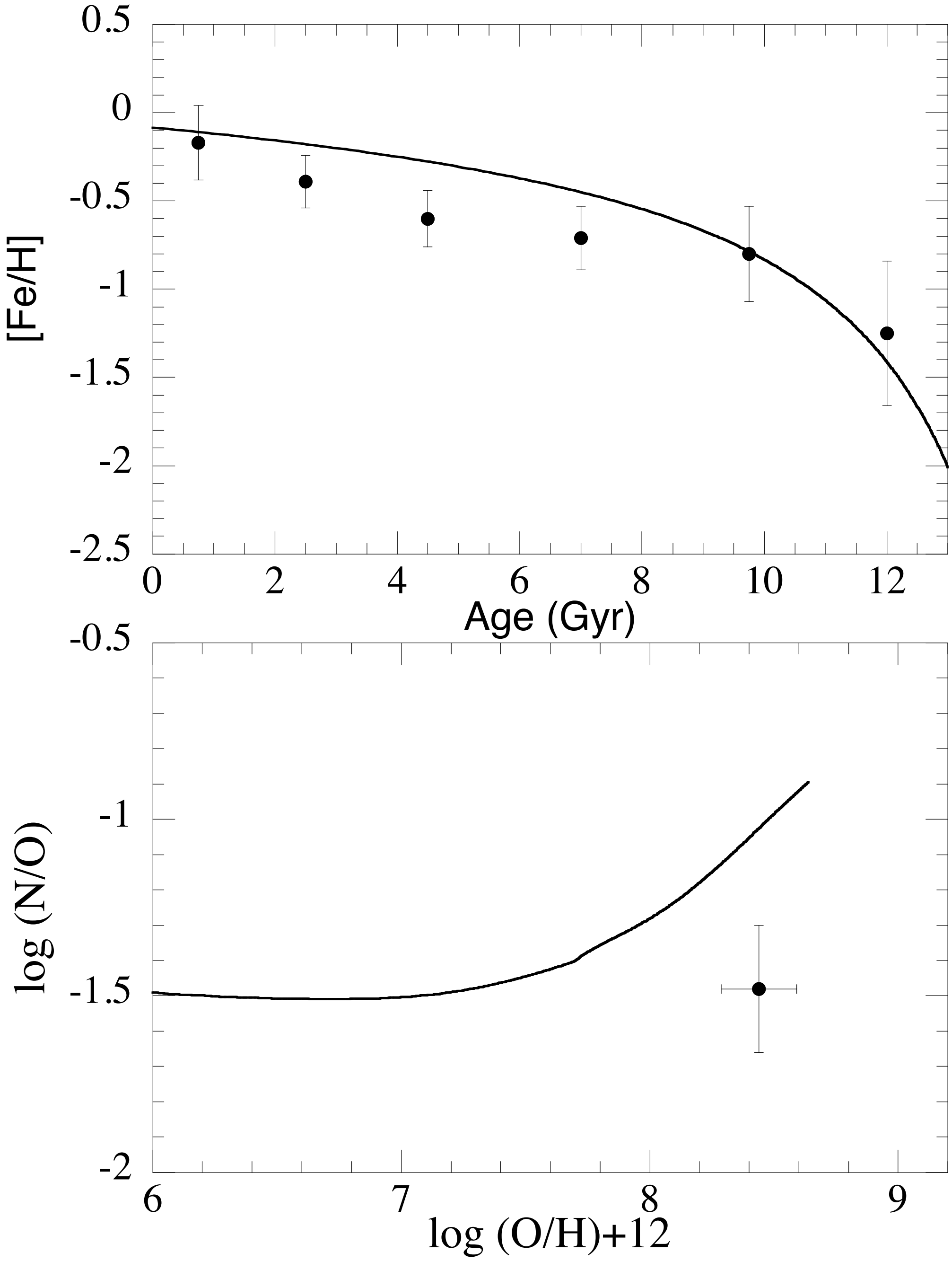

Fig. 6.— The upper panels show the observed age-metallicity relationship of stars in the LMC (filled circles with error bars) and the simulated one based on the standard one-zone chemical evolution model (solid line). The lower panel shows the time evolution of log(N/O) as a function of log(O/H)+12 for the adopted one-zone chemical evolution model with a reasonable IMF. The lower log(O/H)+12 means younger LMC in this model. For comparison, the observed value is shown as a filled circle with error bars. The details of the observations and the simulated models are given in Tsujimoto & Bekki (2009, 2010). Clearly the modeled present LMC (at log(O/H)+12$\sim$ 8.4) shows much larger log(N/O) in comparison with the observation.